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Bethesda, Md. 20084

A METHOD FOR PREDICTING THE OFF-DESIGN PERFORMANCE OF CLOSED-BRAYTON-CYCLE ENGINES

By
Donald T. Knauss

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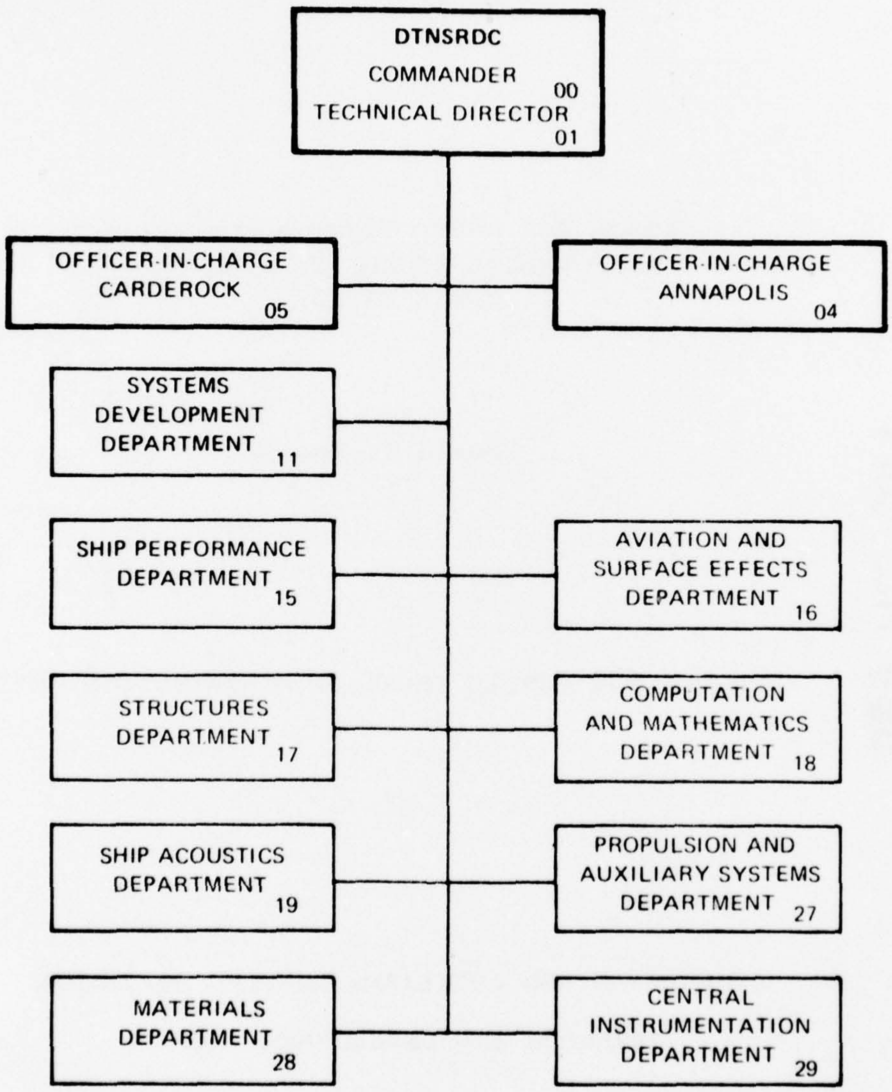

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(Author)

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LIST OF ABBREVIATIONS

CBC	Closed-Brayton-cycle
C	Celsius
F	Fahrenheit
hp	Horsepower
in^2	Square inch
kg/sec	Kilogram per second
kW	Kilowatt
kPa	Kilopascal
lb/sec	Pounds per second
MPa	Megapascal
NEPCOMP	Navy Engine Performance Computer Program
psia	Pounds per square inch absolute
rpm	Revolutions per minute
viz	Namely

$$CF = \text{corrected flow} = \frac{W\sqrt{T_t},}{P_t} \quad \frac{lb_m \; {}^\circ R^{1/2} \; in.^2}{sec \; lb_f} \quad \left(\frac{kg \; {}^\circ K^{1/2}}{sec \; MPa}\right)$$

ICF = interface corrected flow

N = shaft speed, rpm

P = pressure, psia (MPa)

P_{ref} = 14.7 psia (0.101 MPa)

T = temperature, F (C)

T_{ref} = 518.7 F (287.8 K)

W = mass flow, lb_m/sec (kg/sec)

δ = P/P_{ref}

η_{mech} = mechanical efficiency due to shaft losses

η_{Th} = gross thermal efficiency, %

θ = T/T_{ref}

SUBSCRIPTS

t = stagnation condition

ref = reference value

number subscripts represent the flow stations defined in Figure 4.

ABSTRACT

The development of a computer program for predicting the off-design performance of closed-Brayton-cycle engines is discussed. The approach to the problem was to modify an existing Navy-developed open-cycle gas turbine engine program. The characteristics of the existing program and the various techniques used in "closing the cycle" are discussed, along with modification of the existing program subroutines and the development of new program controls. The requirements for modeling the component performance and the mechanical losses associated with a laboratory engine under test are considered. Engine off-design performance predictions obtained by the above method are compared with those of the engine manufacturer. Further comparisons are made between the computed results and those obtained from actual engine test data. Some estimates of the errors associated with the engine data-acquisition system are presented. A discussion of multiparameter performance mapping is included, and the basic procedure used in developing a four-parameter map of the closed-Brayton-cycle laboratory engine is described. The map obtained by this method is presented and discussed.

ADMINISTRATIVE INFORMATION

This work was jointly sponsored by the Defense Advanced Research Projects Agency, Dr. Philip Selwyn, Program Manager, and Naval Sea Systems Command (SEA 0331), Mr. Charles Miller, Program Manager. The work was performed in the Gas Turbines Branch of the Power Systems Division, Propulsion and Auxiliary Systems Department, under Work Unit 1-2721-152.

INTRODUCTION

Interest in the CBC* as an energy converter for underwater applications has increased as a result of technology advances in both aerospace and stationary, land-based applications.

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*Definitions of abbreviations appear on page v.

A brief review of its development is provided by Woodward.[1*] In regard to underwater-vehicle applications, DTNSRDC, through support from DARPA and NAVSEA, has been engaged in a technology development program which is aimed at demonstrating the practicability of the CBC as a prime mover for small special-purpose underwater vehicles. This development program, which incorporates both analytical and experimental investigations, is exploiting the multiheat source capability of the engine, its inherently high part-power thermal efficiency, and quiet operation. In parallel with this effort, the program has the objective of showing the potential of the engine/heat source for achieving relatively low weight and volume for closed systems.

The analytical phase of this program has included the investigation of methods for predicting engine performance under various off-design conditions. Some other investigations which include Brayton-cycle performance estimates are listed in the references.[2-14] However, none of these provides a detailed description of a specific procedure for making closed-cycle off-design predictions. This report presents the details of a mathematical technique which can solve such problems; it has the capability for simulating a broad variety of closed-Brayton-engine configurations.

ENGINE SYSTEM DESCRIPTION

The general schematic of a CBC, together with its associated temperature-entropy diagram, is shown in Figure 1. The closed working-loop consists of a rotating unit which compresses and expands the working fluid, a heat source, recuperator, and cooler. The single-shaft laboratory engine under development at DTNSRDC (shown in Figure 2) has a centrifugal compressor and turbine and uses argon as the working fluid.

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*A complete listing of references is given on page 27.

Ultimately, the performance can be upgraded by the use of a xenon-helium mixture as the working fluid.

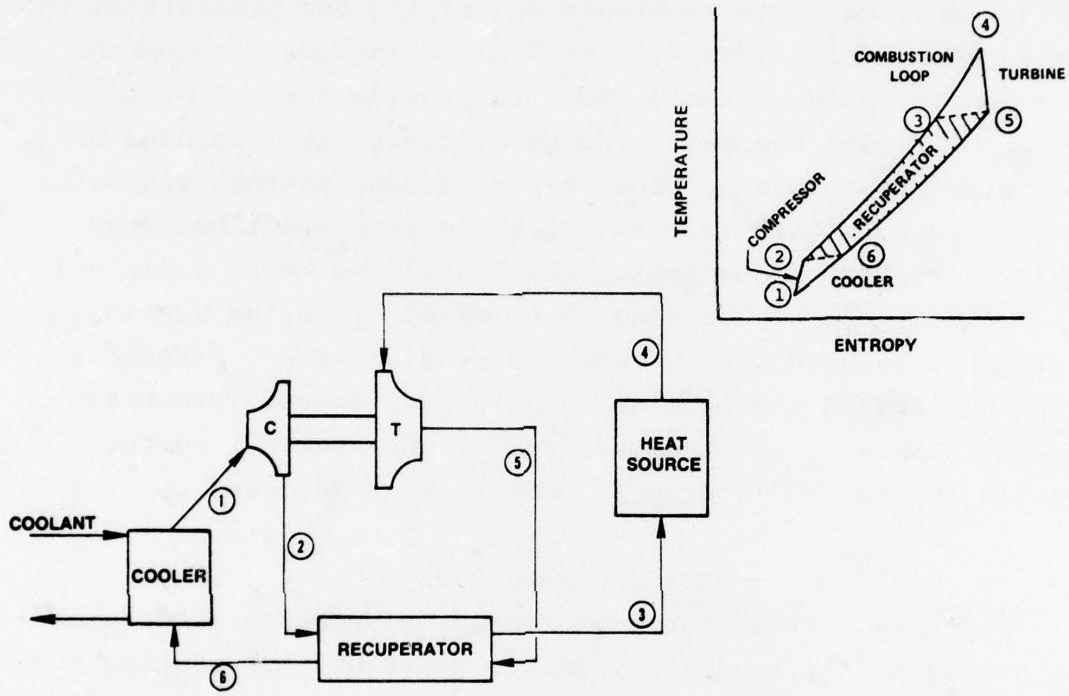

Figure 1 - Schematic and Thermodynamic Diagrams for a Closed-Brayton-Cycle Engine

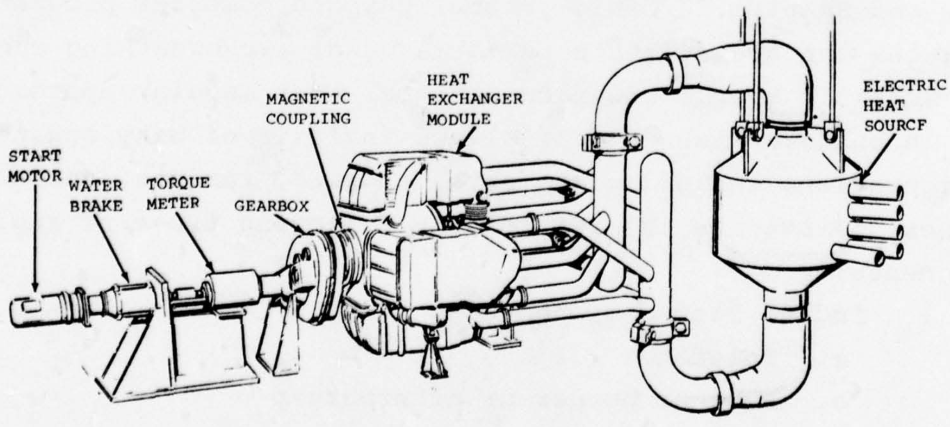

Figure 2 - 30-Kilowatt Laboratory-Brayton-Engine System

In the basic mode of engine operation, both shaft speed and turbine-inlet temperature are held constant. Variation of the power output is achieved by varying the pressure of the gas in the working loop. Present plans include development of a continuously variable drive to provide control of output speed. Although the basic engine configuration includes an electrical heat source, other types of heat sources are being fabricated for retrofit. All of the engine shaft bearings employ a rather unique system which utilizes metal foils and gas cooling; the gas cooling is provided by engine working fluid that is bled off the compressor discharge. After circulating through the bearings, the gas is dumped into the turbine flow at a point downstream of the stator. Further details on the CBC program at DTNSRDC were reported by Duvall.[15]

MODELING PROCEDURE

Since CBC off-design performance calculation procedures are not generally available, it was apparent that such methods would either have to be developed or derived from an existing open-cycle engine program. A search for such a program revealed the existence of a very flexible open-cycle routine called NEPCOMP. The details of this program are described by Caddy and Shapiro.[16] This general purpose computer program simulates the steady-state performance of air-breathing engines with multiple spools and flow streams. The modular approach used in building the program allows analysis of many engine configurations including augmented engines, ramjets, and shaft engines. Provision is made for the following types of engine components:

1. Engine Flow Components
    a. Inlet
    b. Duct or burner or afterburner
    c. Compressor
    d. Turbine
    e. Flow splitter or bypass

f. Flow mixer

g. Nozzle

h. Recuperator

2. Engine Mechanical Components

a. Loads

b. Shafts

The first class of mechanical components permits simulation of fixed or variable horsepowers that may be absorbed through engine output shafts; this class consists of the load components such as electric generators, fuel pumps, and auxiliary power units. The second class of mechanical components permits the simulation of physical connections (and associated frictional losses) between rotating engine components. The rotating components may be either flow components or loads. Mechanical components permit application of certain mathematical constraints on engine cycle calculations which will ensure that the net horsepower imbalance between any pair of physically connected components will be either zero (for the point-design mode) or a very small value (for the off-design mode). Thus, mechanical components account for all of the power absorbed throughout the engine cycle and, consequently, influence the calculations within engine flow components.

One other type of input required by NEPCOMP is the control element. Since the solution for engine performance is obtained by an iterative process, controls are generally needed to establish the proper iteration variables; moreover, they provide a means for altering the computational procedures to meet specific objectives. Each control element specifies both independent and dependent variables and imposes a specific constraint on the value of the dependent variable. Because of the complex nature of the iteration process, a judicious choice for each of these variables is required to guarantee solution convergence. For example, one might wish to vary the shaft revolutions per minute to achieve a balance between the horsepower required by the compressor and the horsepower produced by the turbine.

As many as 30 individual components can be simulated by NEPCOMP, but in any given simulation, no more than 20 of each type of component may be used, excluding control elements. The program permits up to 15 control elements per simulation.

Briefly, the modeling procedure begins with the layout of a flow diagram which shows the engine flow components connected in the same order as the engine it simulates. Integer component reference numbers are assigned in a consecutive sequence beginning with the number one. Wherever weight flow enters or leaves a component, an integer flow station number is assigned in consecutive sequence. NEPCOMP makes a "pass" through the engine by starting at each inlet and calculating the gas properties at each flow station in the configuration.

The computer program has two basic modes of operation, "point-design" and "off-design". A point-design calculation is used to obtain a solution at just one operating point; this may be done with or without component maps. Without maps, the program simply calculates each thermodynamic state point in the engine cycle. Equilibrium weight flow is implied in all point-design solutions. Since the inlet flow area of each component is sized by the program to pass whatever corrected flow enters it, the corrected flow error at each component interface is automatically zero. In the point-design mode, the horsepower imbalance on each shaft is eliminated by adjusting the pressure ratio of each turbine. The point-design mode also provides the sizing information necessary for the off-design mode. When component maps are used, the point-design output also provides necessary map scaling factors. This capability is achieved by internal routines that locate the operating point of each component on its respective map and calculate the appropriate scaling factor for that map. Control elements are optional in the point-design solution for many engine configurations.

After the appropriate scaling factors and areas for each component have been obtained from the point-design mode, the

off-design performance can be calculated. At least some component maps are required, and unlike point-design calculations, control elements must be used to obtain the conditions of equilibrium weight flow and balanced shaft horsepower. The relationship between the independent and dependent variables defined by these controls is generally nonlinear, and, since the dependent variables cannot be explicitly defined in terms of the independent variables, no direct solution to the problem is possible. The iterative solution technique used by NEPCOMP is called the modified Newton-Raphson method.

The interrelationships between the various subroutines and functions used by NEPCOMP are shown in Figure 3. The arrows indicate the direction of interrogation. A response in the opposite direction is associated with each of them. A brief description of each subroutine and function appears in Table 1.

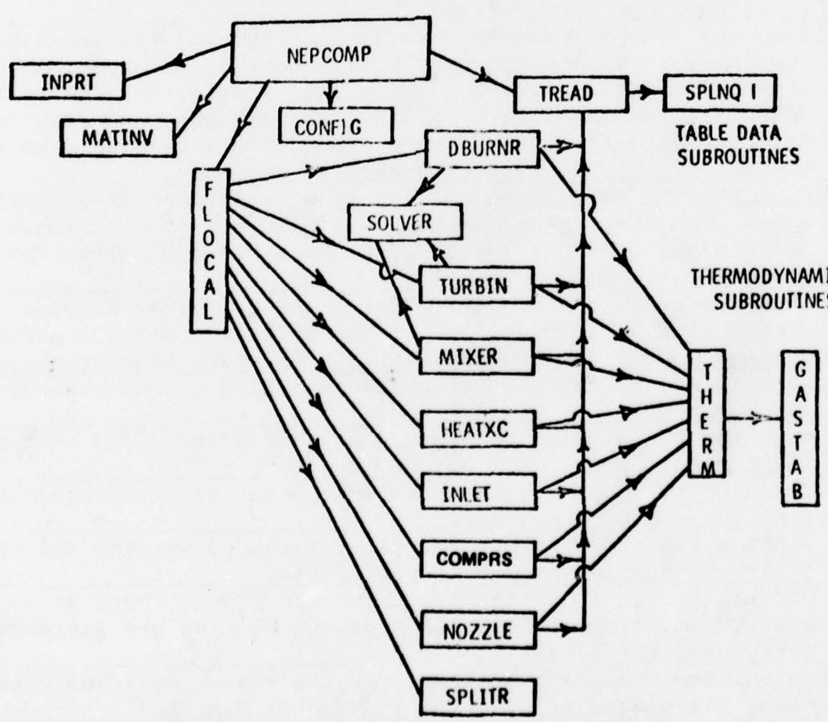

Figure 3 - Interrelationships Between the NEPCOMP Subroutines and Functions

TABLE 1
DESCRIPTION OF NEPCOMP SUBROUTINES AND FUNCTIONS

Name	Description
INPRT	Controls the printing of all the input and output data.
CONFIG	Processes the engine configuration data; flow components are assembled from inlets to nozzles as they would appear in the flow stream inside the engine being simulated; determines the order of calculations made in the convergence process.
TREAD	Effects the input and storage of table data representing engine component characteristics; upon the request of another subroutine, it interrogates this data, with the aid of function SPLNQ1, at any time during the cycle calculations.
SPLNQ1	Interpolates or extrapolates tabular data.
MATINV	Calculates the inverse of the matrix of partial derivatives; this provides the rates of change of the interface errors with respect to each of the unknowns specified in the problem. The procedure is basic to the solution-convergence technique.
FLOCAL	Sequentially calls the flow component subroutines to perform engine cycle calculations for the configuration being simulated.
DBURNR	Calculates the performance characteristics of all duct-type components including "cold-duct" pressure drops, and engine burner, or afterburner performance.
TURBIN	Executes the performance calculations for all turbine-type engine components. Weight flow may enter the turbine by a main entrance and a bleed flow entrance. When this occurs, turbine entrance bleed flow is mixed with the turbine main entrance flow on a flow-weighted enthalpy basis. This procedure is then used to determine the total temperature at the turbine entrance.
MIXER	Performs the calculation of the flow conditions in a component where two entering gas streams are combined into a single exiting gas stream; provides a static pressure balance across the main and secondary streams.
SOLVER	Uses iterative techniques to solve one-degree-of-freedom problems. Convergence is achieved by a slope-intercept method. SOLVER is called upon by the TURBIN, DBURNR, and MIXER subroutines.
HEATXC	Calculates the performance characteristics of recuperator-type components.
INLET	Computes the airflow conditions at the entrance and exit of an inlet component.
COMPRS	Executes the performance calculations for all compressor or fan-type engine components.
NOZZLE	Handles the calculations for determining convergent and convergent-divergent nozzle velocity coefficients.
SPLITR	Calculates the flow conditions in a component where an entering gas stream is split into two separate exiting gas streams; primarily used for bypass flow ducts.
GASTAB	Calculates the gas properties for the engine cycle calculations using the procedure given in the User's Manual.[17]
THERM	Provides the interface between the subroutines in NEPCOMP and subroutine GASTAB; sets up the input gas property parameters necessary to use the GASTAB subroutine.

The CBC engine chosen for simulation was a 30-kW laboratory engine operating at the Center. This engine, which was described earlier, was designed and built, under contract, by the AiResearch Manufacturing Company of Arizona. The engine schematic, based on the NEPCOMP simulation format, is shown in Figure 4. It is seen that the flow components (1 through 12) are connected by solid lines whereas mechanical components (13 and 14) are connected by broken lines. The alternating dash lines are control connections to a component or station number that has one of its parameters coupled to a particular control element (15 through 20). These control lines are identified as to the nature of the controlled variable, i.e., independent (I) or dependent (D).

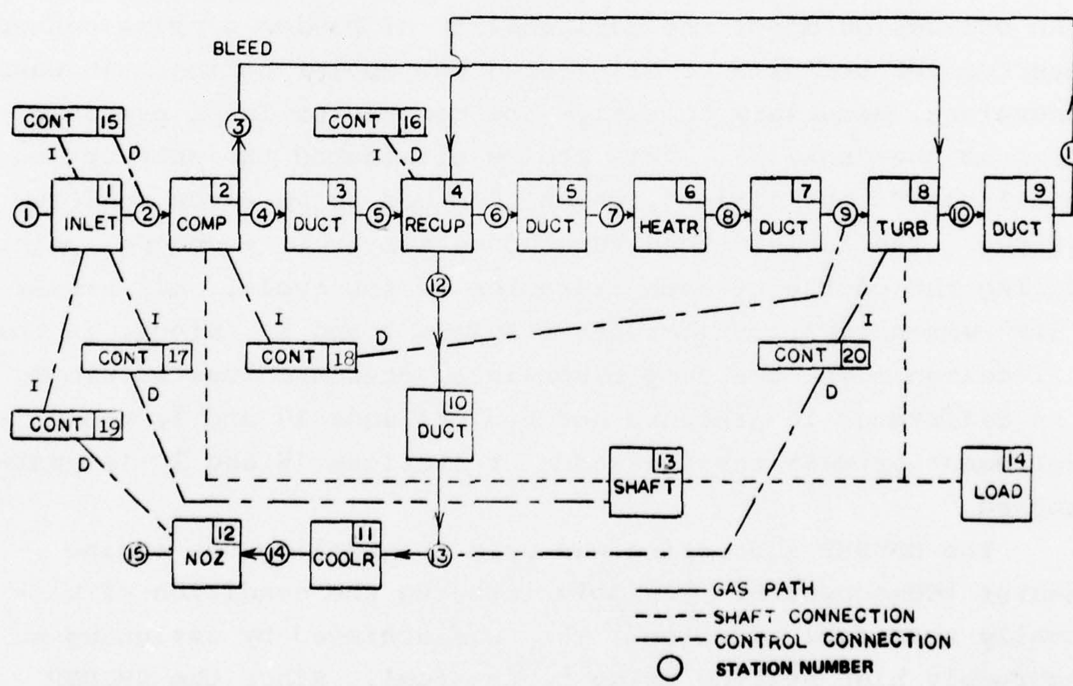

Figure 4 - NEPCOMP Configuration
for the CBC Laboratory Engine

Two components, related only to open-cycle engines, had to be retained because of certain essential program-control functions. One such component is the nozzle and its associated pressure loss, which, for modeling purposes, had to be assigned a pressure loss associated with the laboratory engine. This assignment was governed by the NEPCOMP requirement that the discharge pressure of the "nozzle" (Component 12, Figure 4) be equal to the pressure at the engine "inlet" (Component 1, Figure 4). Although the "inlet" is not an essential component in closed-cycle engines, it does have a basic control function in NEPCOMP. However, unlike the "nozzle," it could be given either a laboratory-engine assignment or no-loss status.

The possible choices for the "nozzle" pseudo role were limited to either the cooler or compressor-inlet pressure loss. Since the "nozzle" pressure loss becomes a floating quantity in the off-design mode, the desirability of having precise control over cooler performance eliminated the cooler option. It was, therefore, necessary to assign the compressor-inlet pressure loss to the "nozzle". This choice eliminated the only option available to the "inlet", which then had to be given no-loss status. The "inlet" then functioned simply as a control point during the course of each iteration of the cycle. All properties remain invariant between Stations 1 and 2. Since, in the off-design mode, the compressor-inlet pressure loss is simply the difference in pressure between stations 14 and 1, the agreement between the pressures at Stations 15 and 1 is guaranteed.

The DBURNR subroutine was used in modeling the engine heater (Component 6) by simply imposing the condition of virtually zero fuel addition. This was achieved by assigning an extremely high heating value to the fuel. Since the DBURNR subroutine also simulates duct pressure losses, all such losses occurring in the engine, as identified in Table 2, were also assigned to this subroutine. It should be noted that the cooler core (Component 11) is included in this list since

NEPCOMP did not provide a subroutine for evaluating the performance of external heat exchangers. The modification of DBURNR to accommodate the cooler is described below. However, it should be noted that this circumstance only permits simulation of flow properties on the gas side of the cooler and does not allow the internal calculation of compressor-inlet temperature. Compressor-inlet temperature is, therefore, a fixed input quantity which cannot be varied by the program. Nevertheless, whenever a known variation is available for this temperature, NEPCOMP will provide the proper temperature drop across the cooler by calculating the flow conditions at Station 12. This is possible because agreement between the temperatures at Stations 15 and 1 is not required.

TABLE 2 - ENGINE DUCT PRESSURE LOSSES SIMULATED BY THE DBURNR SUBROUTINE

Component No. Figure 4	Pressure-Drop Simulation
3	Compressor Discharge
5	Heater Inlet
7	Turbine Inlet
9	Turbine Discharge
10	Cooler Inlet
11	Cooler Core

A complete description of the independent and dependent variables assigned to the control elements is given in Table 3. These controls instruct the program to vary the independent variable until the error in the specified value of the dependent variable does not exceed a certain magnitude. Table 3 also indicates the activity of the control in either the point-design or off-design mode.

In addition to the configurational problems described above, other problems were encountered in adapting NEPCOMP to closed-cycle engines. These were related to incompatibilities in the structure of some of the program subroutines given in Figure 3. Two revisions had to be made in subroutine FLOCAL.

TABLE 3 - DESCRIPTION OF PROGRAM CONTROLS

Control No.	Activity	Independent Variable	Dependent Variable
15	+	Mass flow through Component 1.	ICF ERROR at flow Station 2.
16	*,+	Temperature rise across the cold side of Component 4.	Deviation from temperature rise found in previous iteration.
17	+	Stagnation pressure in Component 1.	Unbalanced horsepowe on Component 13.
18	+	A coordinate used in locating the compressor state-point	ICF ERROR at flow Station 9.
19	*	Mass flow through Component 1	Pressure ratio P_{14}/P_{15} across Component 12.
20	+	Pressure ratio P_9/P_{10} across Component 8.	ICF ERROR at flow Station 13.

ICF ERROR = $(CF)_{UPSTREAM} - (CF)_{DOWNSTREAM}$
*Point-Design Mode
+Off-Design Mode

One of these revisions was the introduction of a new method for modeling engine shaft losses. In its original form, NEPCOMP was only capable of utilizing fixed-input mechanical efficiencies to account for such losses. This procedure was totally inadequate for CBC engines employing foil-type gas bearings in which the losses are known to be a function of compressor-discharge pressure and shaft speed. In incorporating such a model into NEPCOMP, the fixed-input mechanical efficiency served only as a trial value to initiate the cycle calculations. During the cycle calculations, this trial value was replaced by a new value found by evaluating the new mathematical expression which had been programmed into subroutine FLOCAL. This expression is functionally represented by

$$\eta_{mech} = \frac{\text{Load}}{\text{Load} + L_B + L_{F.S.}}$$

where $L_{F.S.}$ is the face-seal loss, which is assumed constant, and L_B, the bearing loss, is given as:

$$L_B = \text{func}\left[\left(\frac{P}{P_{D.P.}}\right)_4,\left(\frac{N}{N_{D.P.}}\right)\right]$$

with subscript D.P. representing design-point conditions. The general functional relationship for L_B and its specific dependence on speed were provided by the AiResearch Manufacturing Company. In establishing the dependence of L_B on compressor-discharge pressure, it was necessary to derive an empirical expression based on test data obtained from AiResearch.

A second change in subroutine FLOCAL specified the method for calculating an important closed-cycle performance parameter, viz, thermal efficiency. This parameter was not an output quantity provided by basic NEPCOMP. The eventual print-out of thermal efficiency required modification of subroutine INPRT.

Since, as mentioned above, NEPCOMP did not provide a subroutine for evaluating the performance of external heat exchangers, a somewhat more extensive revision of the DBURNR subroutine was necessary to effect the calculation of the cooler pressure drop. This is because the existing tabular input format employed by DBURNR in evaluating duct pressure losses was incompatible with the format of the cooler performaance maps provided by the engine manufacturer. Nevertheless, because of the inherent flexibility in the program structure, this problem could be resolved in a straightforward manner. It was only necessary to introduce a conditional branch in DBURNR, called by Component 11, which would lead to an alternate table-look-up procedure. This new procedure specified the independent variables of the existing cooler maps. It replaced the inlet corrected flow with referred flow and introduced the inlet total pressure as a second independent variable. The tabular input array was then functionally represented by:

$$\Delta P/P = \text{func}\left[\left(\frac{W\sqrt{\theta}}{\delta}\right)_{12}, (P_t)_{12}\right]$$

In subroutine HEATXC, which is called upon by Component 4, a similar map compatibility problem was encountered in calculating the pressure drops on both sides of the recuperator, except that the conditional branch was not required. The new relations for these quantities took the form

$$(\Delta P/P)_{cold} = \text{func}\left[\left(\frac{W\sqrt{\theta}}{\delta}\right)_{4}, (P_t)_{4}\right]$$

and

$$(\Delta P/P)_{hot} = \text{func}\left[\left(\frac{W\sqrt{\theta}}{\delta}\right)_{10}, (P_t)_{10}\right]$$

At a later point in the same subroutine, a similar revision of the table-loop-up procedure for recuperator effectiveness was also necessary for the same reason as above. In this instance, the cold-side mass flow and the hot-side/cold-side mass flow ratio were replaced by the cold-side-inlet referred flow and total pressure. Functionally,

$$\epsilon = \text{func}\left[\left(\frac{W\sqrt{\theta}}{\delta}\right)_{4}, (P_t)_{4}\right]$$

RESULTS

Sample results of the modified NEPCOMP program (CBC NEPCOMP) are presented in Figure 5, which shows gross thermal efficiency as a function of shaft power. For comparison, an independent off-design prediction provided by the AiResearch Manufacturing Company, the designer and builder of the laboratory engine, is also shown. Both curves are based on the design-point conditions given in Table 4, where the asterisks identify the NEPCOMP inputs which must be precisely specified. As in the normal mode of engine operation, turbine-inlet temperature, shaft

speed, and bleed fraction are held constant over all power levels. In modeling the off-design performance, a predicted variation of compressor-inlet temperature with power was used.

The performance curves shown in Figure 5 are typical of CBC engines with their characteristically high part-power efficiency. The engine shows a peak efficiency above 32 percent occurring at 20-22 hp (15-16 kilowatt).

Although not shown, the efficiency gradually decreases as the power is reduced below 15-hp (11-kilowatt). Accurate estimates for this portion of the curve are not available due to the limitations on the component maps utilized. Below 15-hp (11-kW), the values of the map parameters are significantly outside the map boundaries, and the resulting extrapolations are in error by more than 10 percent.

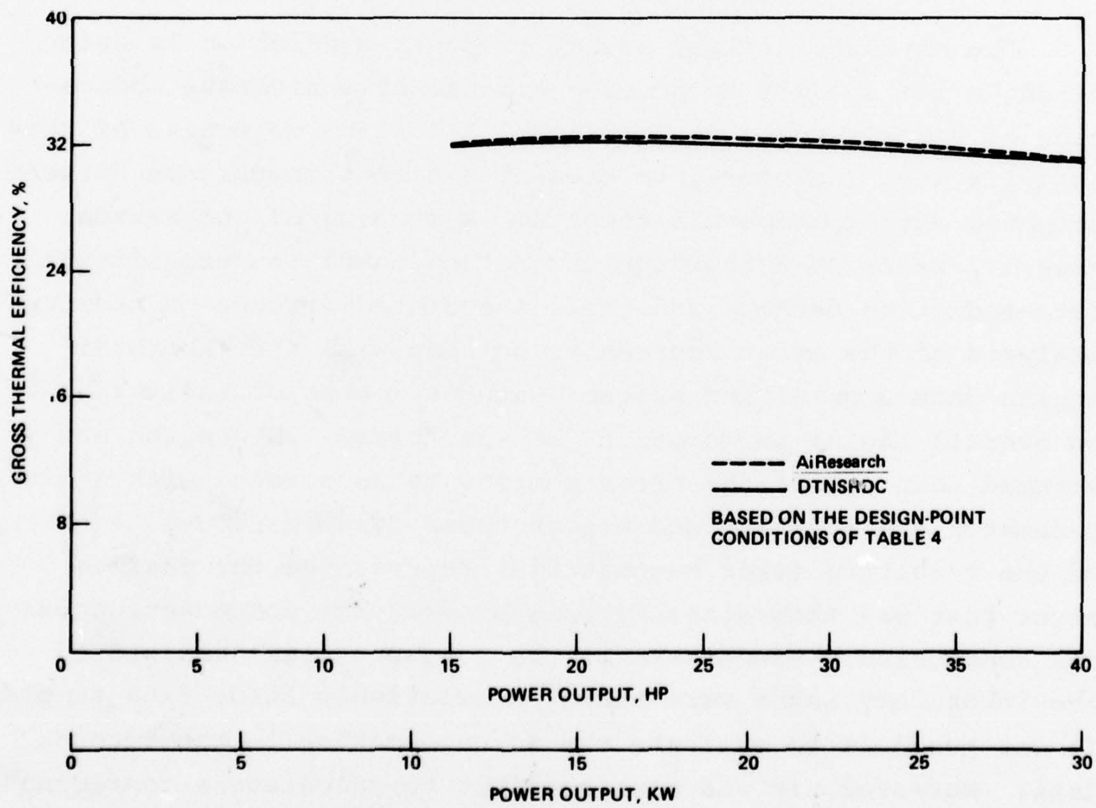

Figure 5 - Computer Predictions of the Off-Design Performance of the CCPS40-1 Engine

TABLE 4 - PREDICTED DESIGN-POINT CONDITIONS FOR THE LABORATORY ENGINE WITH ARGON WORKING FLUID

Parameter	Value
Shaft Speed, rpm*	52,000
Bearing Losses, kW*	0.706
Face-Seal Loss, kW*	0.400
Output Power, kW*	30.0
Compressor-Inlet Temperature, F (C)*	85.7 (29.8)[1]
Turbine-Inlet Temperature, F (C)*	1500 (815)
Gross Cycle Efficiency, %	31.0
Compressor Mass Flow, lb/sec (kg/sec)	1.51 (0.685)
Compressor-Bleed Fraction, %*	2.0
Recuperator Effectiveness, %	85.5
Cooler Effectiveness, %	95.5
Compressor Adiabatic Efficiency, %	78.7
Turbine Adiabatic Efficiency, %	90.7

*Input parameters.

[1]Based on cooling-water inlet conditions of 70 F (21.1 C) and 1.47 pps (0.667 kg/sec).

The ultimate utility of any computer prediction is determined by its ability to provide a reasonably accurate indication of actual engine performance. A further objective of this analysis was, therefore, to present a direct comparison between computed and experimental results. A meaningful comparison, however, rests on a thorough understanding of the experimental data-reduction methods and their associated errors. A thorough analysis of the error sources associated with the laboratory-engine data acquisition system, with estimates of their impact on overall engine performance, was performed. Since the analysis assumed that all of the error components associated with a given parameter are additive and are at their maximum values, each of the resulting error quantitities represented the maximum error that was theoretically possible. Error compensation was not considered. Since some of the load profiles obtained in the laboratory tests were based on relatively large data samples, it was possible to evaluate the actual scatter in the recorded data. Moreover, it was also possible to calculate a confidence interval of the true mean value. A discussion of this procedure and the results is given later in the text.

A direct comparison was made between actual engine performance and the performance predicted by NEPCOMP. The input data for the NEPCOMP simulation were based solely on measured engine data. Figure 6 presents a comparison between the "MOD-O" engine test data and the corresponding NEPCOMP simulation. The "MOD-O" designation refers to the initial unmodified configuration of the engine which included a rectangular recuperator.[15] In the MOD-1 version of the engine, the rectangular recuperator was replaced by an annular recuperator which demonstrated an advanced packaging technique for achieving higher loop pressures and improved power densities. From calculations based on actual recuperator performance, it was observed that the MOD-O recuperator exceeded its design predictions. Since the recuperator performance maps incorporated into NEPCOMP were based on predicted performance, the discrepancy between the two curves of Figure 6 should be somewhat larger. It can be seen that the deviations are, in fact, quite small with maximum differences of approximately 2 1/2 percent of the 31 percent design efficiency occurring at the extremities of the curves.

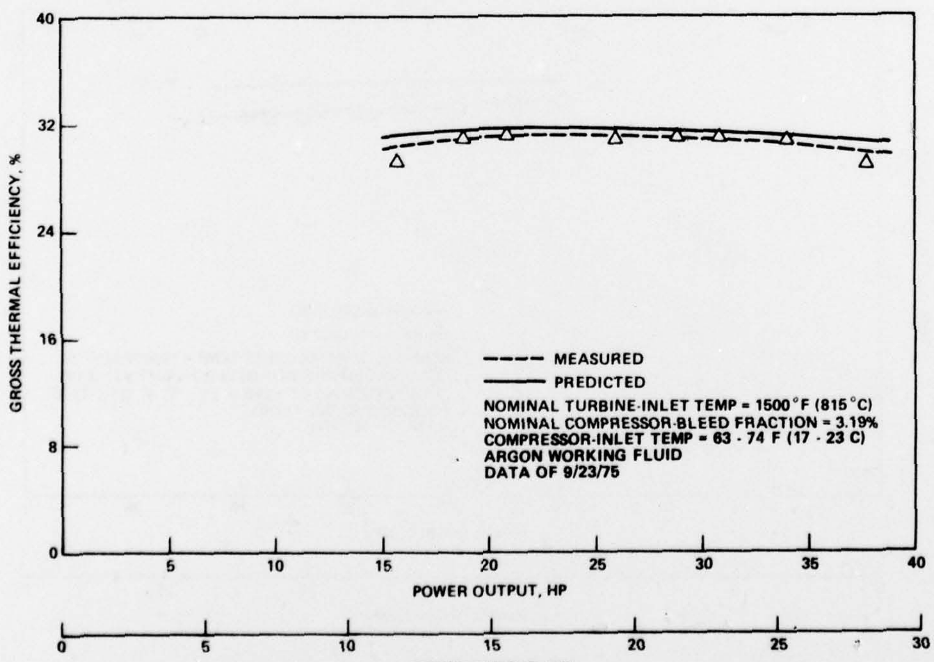

Figure 6 - Comparison Between the Measured Performance and the Predicted Performance of the MOD-O Engine at 52,000 RPM

The influence of engine shaft speed on the accuracy of the NEPCOMP simulation was also investigated. In addition to its effect on compressor and turbine performance, shaft speed also appears as a parameter in the bearing loss model. An evaluation of these effects was obtained by generating load profiles, similar to Figure 6, at two different shaft speeds. Since the MOD-1 engine configuration provided the most extensive test data at off-design speeds, the computer comparisons for speed effects were based on the MOD-1 data. Figure 7 shows a comparison between the measured and predicted performances at the design shaft speed. These results reflect the change in engine performance due to the annular recuperator which operated below its predicted performance. The resulting deviation between the curves is therefore somewhat overestimated with the range of the values being 5 to 8 percent.

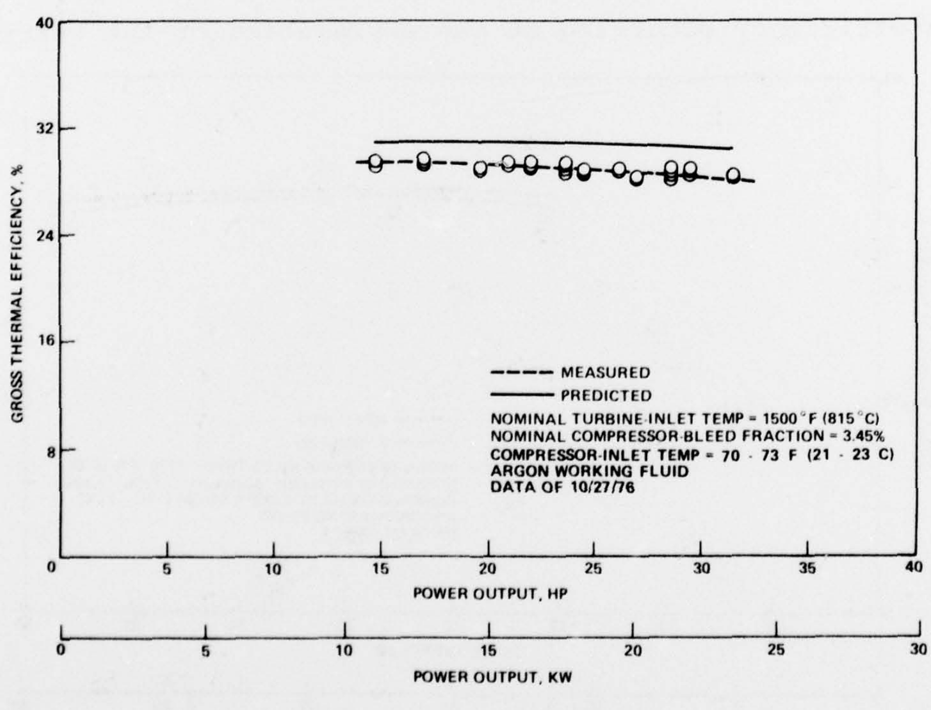

Figure 7 - Comparison Between the Measured Performance and the Predicted Performance of the MOD-1 Engine at 52,000 RPM

The much larger number of data points associated with Figure 7 afforded a direct estimate of the error associated with the experimental determination of thermal efficiency. Since the data of Figure 7 exhibit a general increase in efficiency as the load is reduced, the maximum error must be determined at the load which exhibits the maximum scatter. If the best-fit curve of Figure 7 is taken to be a true-value curve, the maximum error, represented by the 16 data points at about 29 hp (21.6 kW), is calculated to be ±2 percent. A somewhat larger scatter would be expected if a larger data sample were available. Nevertheless, a far more meaningful measure of data accuracy is the confidence interval of the true mean value, which gives the probability that the difference between the mean value of a data sample and the true mean value of the population will be less than a certain prescribed value. Since, in this case, the true mean value varies with the load, the standard deviation was calculated for the data sample associated with each load. By applying each of these results to the Student-t distribution for small samples, it was possible to obtain a confidence interval that would apply to the entire profile. From this method, it was found that, over the entire load profile, there is 95 percent confidence (or a probability of 0.95) that

$$(\bar{\eta}_{Th})_S - (\bar{\eta}_{Th})_T < \pm 0.34\%$$

where T and S refer to the true mean and sample mean, respectively. Alternatively, it can be stated that there is a 95 percent certainty that, at any given load, the mean value of the measured efficiency will differ from the true value by less than a third of a point. This high degree of experimental accuracy lends considerable credibility to the various data comparisons presented in the text.

In order to evaluate shaft speed effects, another load profile is presented for the same engine configuration operating at a shaft speed of 47,000 rpm. Both the measured and predicted efficiencies are shown in Figure 8. The deviation between the two curves is seen to be nearly identical to that at 52,000 rpm. These results clearly demonstrate NEPCOMP's capability for accurately modeling off-design speeds. In particular, it strongly substantiates the empirical model for shaft losses which was programmed into NEPCOMP.

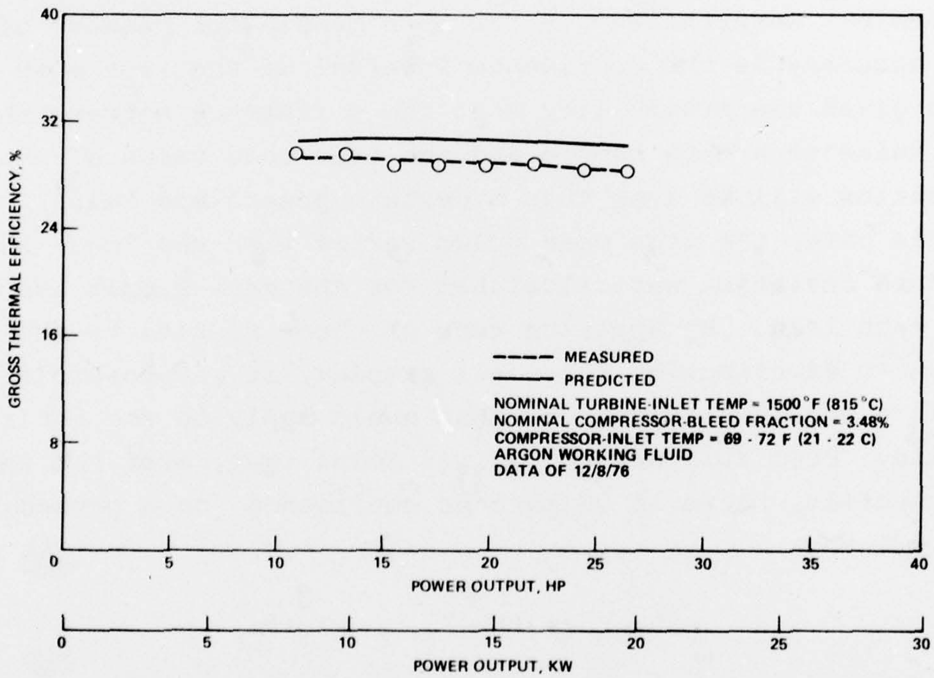

Figure 8 - Comparison Between the Measured Performance and the Predicted Performance of the MOD-1 Engine at 47,000 RPM

In view of the above results, the full potential of NEPCOMP was immediately envisioned. A detailed characterization of the off-design capabilities of the laboratory engine could now be achieved through multiparameter performance mapping. The mapping technique consisted of a four-parameter carpet plot

based on shaft power, shaft speed, compressor-discharge pressure, and gross cycle efficiency.

It was determined that the most convenient way of generating the map was from constant-speed data arrays. However, only certain primary speeds were selected for the constant-speed lines that were actually plotted. The other constant-speed arrays were then used to generate lines of constant efficiency (efficiency islands). The ranges selected for engine speed and discharge pressure were 35,000-55,000 rpm and 10-80 psia (69-552 kPa), respectively. The initial and final points on each of the primary speed lines were found by interpolating for the initial and final pressures.

In generating the map, the following conditions were assumed:

1. Argon working fluid.
2. Constant turbine-inlet temperature = 1500 F (815 C).
3. Constant compressor-bleed fraction = 2.0 percent.
4. At any given load, the influence of shaft speed on compressor-inlet temperature is negligible.

A revision to subroutine INPRT in NEPCOMP effected the generation of the four-parameter data array. Each computer run was for a specified engine speed; the load was varied in 1-hp (0.75-kW) increments over a specified range. For the 55,000 rpm case, this range was 50-1 hp (37-0.75 kilowatt). At the lower speeds it was possible to reduce the upper load limit and still remain above the upper pressure limit. The plotting was accomplished on a Stromberg-Carlson model 4060 computer-recorder. The x and y coordinates used by the recorder were compressor-discharge pressure and load, respectively.

In order to provide a carpet plot bounded by lines of constant speed and constant pressure, it was necessary to shift the origin in the x direction whenever a new speed coordinate was encountered. The amount of the shift depended on the increments chosen for the speed and pressure lines. After generating the primary speed lines, the pressure lines could be generated by simply connecting the intersections formed by the vertical grid

lines and the speed lines. Plotting of the efficiency islands was achieved by a search routine which brackets a specified efficiency and then interpolates for the corresponding load and pressure.

The performance map for the laboratory engine, which was generated by the above method, is shown in Figure 9. It should be noted that this method of map construction greatly facilitates interpolation for the unknown parameters. The map consists of radially oriented lines of constant shaft speed, N, and transverse isobars representing compressor-discharge pressure, P_2. Superimposed on this network is a series of contours representing engine gross thermal efficiency, η_{Th}. Since the speed increments along the isobars and the pressure increments along the speed lines are both constants over the entire map, precise interpolation for both speed and pressure is possible. Due to the limitations imposed by the component performance maps available, the most accurate region of the map lies generally above the 40 psia (276 kPa) isobar. Moreover, uncertainities in the bearing losses and compressor-inlet temperature at speeds far below the design speed might also cause map errors in the vicinity of the lower speed boundary. Nevertheless, it is clearly evident that the degradation of the flat efficiency profile associated with the design speed proceeds very slowly as speed is reduced. In fact, at 35,000 rpm, the efficiency over the load range between 4 and 25 hp (3 and 19kW) never falls below 29 percent. The map further indicates the development of a high-efficiency plateau at approximately 31 percent which is centered on the 40 psia (276 kPa) isobar at 35,000 rpm. This plateau appears to be expanding as speed decreases. The maximum-efficiency island observed in the computer output appears to be centered at a load of 19 hp (14 kW) and a speed of 49,000 rpm; the value recorded was 32.34 percent. It should be noted that other parameters could have been selected for generating the performance map without introducing any added complexity. In the particular case of the CCPS40-1 engine, most of the testing

has been carried out at variable turbine-inlet temperature rather than variable speed. In view of the nature of the existing test data, replacement of the speed parameter by turbine-inlet temperature and design bleed flow by measured bleed flow would allow a very extensive comparison between the predicted and measured engine performance.

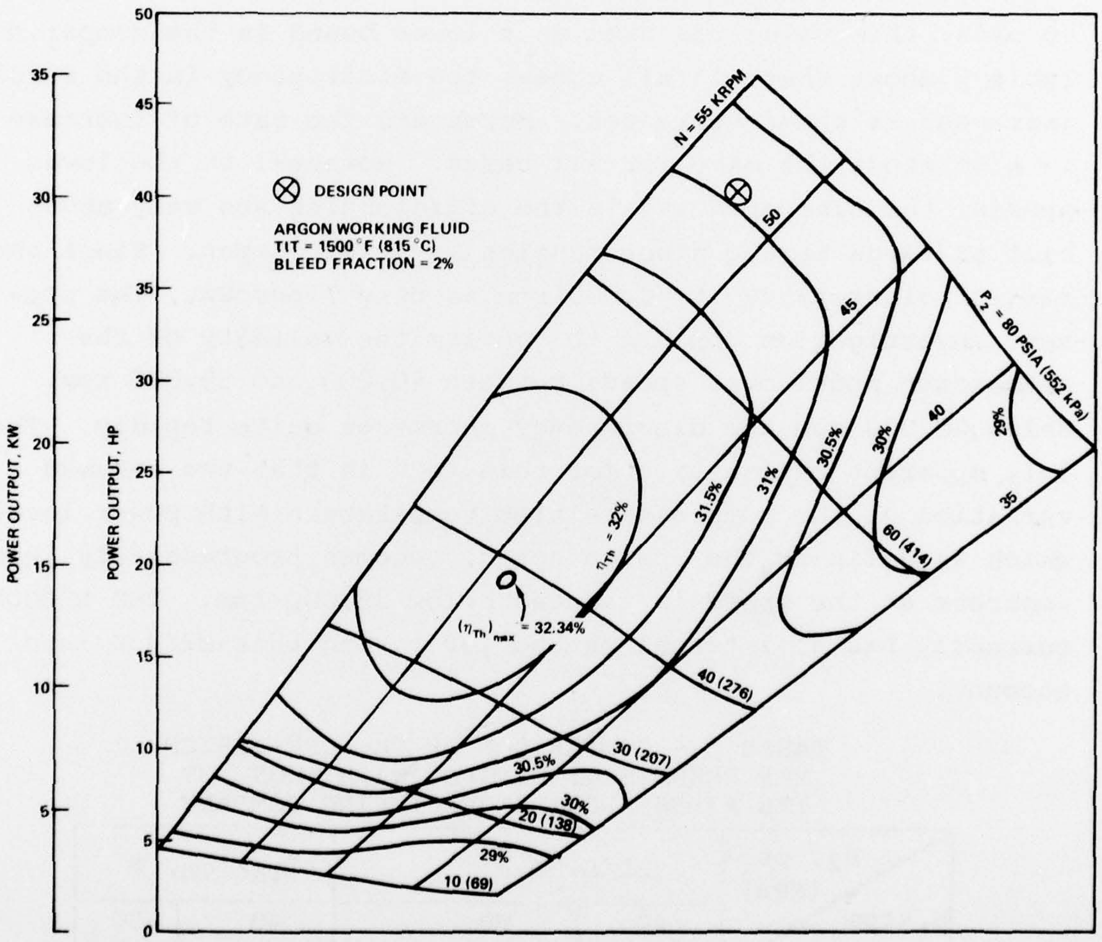

Figure 9 - Computer-Predicted Performance Map of the CCPS40-1 Laboratory Engine

To confirm the influence of shaft speed on engine performance, a comparison between the results of Figure 9 and the predictions of the AiResearch Manufacturing Company has been made. The results of that comparison are presented in Table 5. Both the power output, L, and thermal efficiency were compared at certain compressor-discharge pressures and shaft speeds. It should be noted that a positive sign indicates that the value found by DTNSRDC exceeded the value found by AiResearch. Since the minimum discharge pressure shown on the AiResearch maps was 40 psia, this value was used as a lower bound in the comparison. Table 5 shows that, in all cases, the discrepancy in the results increases as speed decreases. Moreover, the rate of increase is also about the same for all cases. However, at the lower speeds, the discrepancies in the efficiencies are only about half as large as the discrepancies in power output. Since the maximum discrepancy at 40,000 rpm is only 7 percent, the present investigation appears to confirm the validity of the AiResearch model over speeds between 40,000 and 55,000 rpm. Below 40,000 rpm the discrepancy increases quite rapidly. The only apparent explanation for this fact is that the assumed variation of the compressor-inlet temperature with power level, which is valid at the design speed, becomes progressively less accurate as the speed is reduced below 45,000 rpm. CBC NEPCOMP currently has no internal method for taking this effect into account.

TABLE 5 - COMPARISON OF THE OFF-DESIGN MAP RESULTS OF DTNSRDC WITH THOSE OF THE AIRESEARCH MANUFACTURING COMPANY

P_2, psia (MPa) / N, krpm	$\Delta L/L$, %		$\Delta\eta_{Th}/\eta_{Th}$, %	
	40 (276)	80 (552)	40 (276)	80 (552)
35	+17	+25	+9	+11
40	+ 5	+ 7	+2	+ 3
45	+ 2	+ 4	0	+ 1
50	+ 2	0	-1	- 1
55	+ 3	0	0	- 1

CONCLUSIONS AND RECOMMENDATIONS

It has been shown that the basic NEPCOMP computer program, which was designed for use with open-cycle gas-turbine engines, can be modified to provide accurate modeling of small CBC engines. This has been achieved without sacrificing any of the inherent flexibility in handling a variety of engine configurations. It has been demonstrated that the program can be readily modified to provide an output compatible with plotting routines which will generate multiparameter off-design performance maps.

Confident and successful utilization of CBC NEPCOMP in any specific application will depend largely on the availability of accurate component performance maps and the existence of (or capability for developing) accurate mathematical models for all engine losses. With such information in hand, the simple scale-up of the engine discussed above is quite straightforward. More complex configurations would, of course, require more detailed flow diagrams with a larger number of components, control elements, and performance tables. Accurate modeling of engine losses and proper selection of the control elements would probably require the greatest effort. Nevertheless, CBC NEPCOMP should be able to accommodate almost any engine configuration.

Although the utility of CBC NEPCOMP has been demonstrated, there still exists a program requirement which may limit its application. In its present format, the program is incapable of evaluating the thermal performance of the engine cooler. This is due to the lack of a subroutine for handling gas-to-liquid external heat exchangers. As a result, the program requires compressor-inlet temperature as an external input for each operating point; it is not calculated by the program. The development of a cooler subroutine which can generate an exit gas temperature for a given coolant inlet temperature and flow rate is, therefore, highly desirable.

The utility of the program can also be extended by adapting it to other working fluids which may be required by more advanced

engines. Xenon/helium 40 appears to be the prime candidate for these engines. The revision of subroutine THERM for use with Xe/He 40 is, therefore, another worthy endeavor. With the implementation of the above recommendations, CBC NEPCOMP should prove to be a valuable tool in the advancement of CBC technology.

ACKNOWLEDGMENT

The author wishes to acknowledge the earlier work of Dr. Herman Urbach who demonstrated the basic method for extending an open-cycle (NEPCOMP) computer program to closed-cycle configurations.

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